Ultra-Wideband Polarization Conversion Metasurface Based on Topology Optimal Design and Geometry Tailor

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Abstract **─** We presented a topology optimization method based on genetic algorithm (GA) combined geometry tailor scheme (GTS) to realize ultra-wideband polarization conversion metasurfaces (UPCM) in microwave range. The present method takes the connectivity condition of the elements into consideration, thereby resulting in good optimization efficiency. As examples, a UPCM is designed by topology optimization, which is composed of the dielectric substrate sandwiched with patched metallic patterns and continuous metal background. Three plasmon resonances are generated by electric and magnetic resonances, which lead to bandwidth expansion of cross-polarization reflection. The simulated results show that the maximum conversion efficiency is nearly 100% at the three plasmon resonance frequencies and the 3 dB bandwidth range from 5.66 to 24.68 GHz can be achieved for both normally incident x- and y-polarized waves.

Index Terms **─** Genetic Algorithm (GA), geometry tailor, Metamaterials (MMs), metasurface, topology design.

I. INTRODUCTION

Metamaterials (MMs) [1] are artificial media with pitches smaller than the wavelength, which have numerous intriguing artificial electromagnetic responses not attainable with naturally occurring materials. In recent years, many researches worldwide focus on metasurfaces [2], planar metamaterials, which are two-dimension MMs consist of cells repeated periodically throughout a medium. Many MMs have been applied to manipulate electromagnetic characteristics including transmissions and polarizations in sub-wavelength scale, such as polarization manipulation through anisotropic and chiral MMs from microwave terahertz to optical frequency regimes [3], [4].

Recently, the manipulation of polarization is essential for communication, sensing, and other applications. However, narrow working bandwidth is still one of the main problems. In general, the bandwidth can be broadened by multilayer structures. For example, a highly efficient broadband polarization transformation slab has been achieved by stacking twisted complementary circular symmetric split-ring resonators. However, this may be very complicated for irregular shapes and therefore restrict the MMs to regular shape. It is also difficult to find the optimal structures for the MMs using the intuition and empiricism testing. To break through the limitation of bandwidth performances, topology design method was adopted due to the complex nature of the problem, which is based on some kind of intelligent algorithms, such as genetic algorithm (GA).

In this paper, we propose an ultra-wideband polarization conversion metasurfaces (UPCM) design method based on the GA [5] with a geometry tailor scheme (GTS), which is a new type of operator for tailoring pattern shapes. Therefore, the GA with GTS not only can improve the metamaterial topology optimization simulation-efficiency, but also can improve the optimal result searching ability and convergence speed. Firstly, we develop the topology design method with GTS, which operates on matrix of evolution algorithm, as an algorithm operator. The GTS can remove the isolated points in the elements not by natural selection and evolution, but by forcing to wipe them. Secondly, as an example, an UPCM is designed and optimized, then, a comparison between conventional topology method who use natural selection and evolution and topology method with GTS is employed, which demonstrates the topology method with GTS can obtained faster convergence speed of optimization than the conventional topology method. Finally, the effectiveness of the present design method is confirmed by an instance. Both the simulated and optimization results show that the bandwidth is very wide for both x- and y-polarized waves under normal incidence, attaining a 3 dB bandwidth range from 5.66 to 24.68 GHz.

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Furthermore, the efficiency is close to 100% at the three plasmon resonance frequencies, respectively.

II. TOPOLOGY DESIGN METHOD WITH GTS

A. Encoding approach of topology optimization

According to the analysis of GA, the evolutionary structural optimization is just an evolution process under a certain optimization strategy, with which the schema is related to the defining length of the chromosome and thus decides the code number.

Figure 1 shows a single-layer metasurface with a dielectric substrate under consideration and the unit cell of its periodic structure extended infinitely. The unit cell is divided into N×N lattice (10×10 lattice is handled in this paper) to represent the metasurface with an arbitrary element shape in terms of 1s and 0s in the GA. The 1 and 0 correspond to the perfect conductor patch (pixels in Fig. 1) and the free space (blank pixels), respectively. In the present method, the unit-cell geometry tries to work for extensive polarizations bandwidth. So, in the GA, the region is encoded into a 100-bit binary string. The GA starts with a random population and then generates the metasurface element shapes through selection, crossover, mutation and one more operator proposed in this paper. Also the GA keeps the best individual after each generation (elitism strategy). The size of the unit cell must be determined by both p and h, which are encoded by a 18 bit binary string.

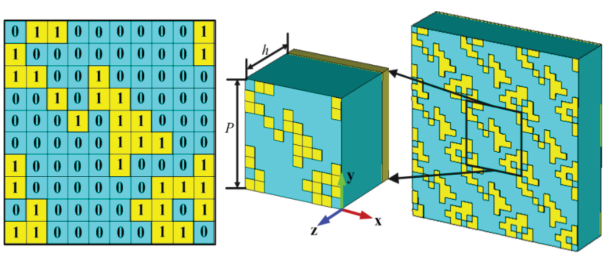

Fig. 1. The configuration and encoding approach of topology design.

B. GTS design

Not only typical GA operators but also a new-type of operator is needed for the optimization design of the MMs element shape taking into account the connectivity condition of the elements. The relation of the basic functions for the analysis with 1s and 0s in the GA is shown in Fig. 1. Most of the metasurface element shapes generated by the GA include the point contact of the isolated lattice points inside the unit cell. If the conductors of an optimized metasurface element have such points, it means that they do not touch each other analytically, which don't contribute to metasurface performance. Therefore, the isolated lattice points should be wiped when fabricating these elements, which can improve the optimization speed and simulation speed. We propose here a GTS, which is a new method for geometry tailor.

Figure 2 shows the flowchart of the optimization-design method based on the GA incorporated with the GTS. This scheme removes the critical points not by natural selective and evolution of GA, but by forcing to eliminate them. The eliminate engine, geometry tailor, works as a sieve, which can search and eliminate the isolated point of geometry matrix. It should be noted here that the GTS can improve optimization simulation efficient by ignoring those isolated pixels which is not contacts physically.

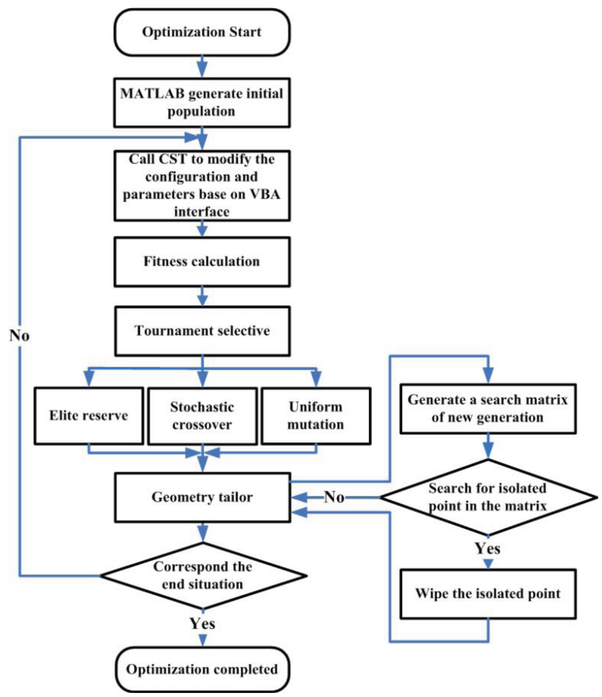

Fig. 2. The flowchart of optimization design with GTS.

C. Fitness function

The numerical simulation is carried out to analyze the reflection behavior of the polarizer with a commercial program, CST MICROWAVE STUDIO 2011 (CST). In the process of simulation, the periodic boundary conditions are used in the x and y directions, and broadband Gaussian-modulated pulse sources with x-polarized and/or y-polarized electric fields are used as the excitation source in the simulation for the linear polarization.

Figure 3 illustrates the comparison between conventional GA and GA with GTS. The fitness function is created according to the goal of expanding polarization bandwidth, which considered the maximal polarization bandwidth and minimal thickness, the more bandwidth the smaller fitness value. In GA, 100 populations are employed in a generation and the selection scheme is tournament selection with two best individuals reproduced, realizing the uniform genetic and mutation process. The crossover probability is set as 0.8, the mutation rate set as 0.01, and the stop condition is related to the fitness goals or is set as truncation limited by the maximum generation number of 30. As shown clearly in Fig. 3, the algorithm convergence speed and stability of UPCM with GTS is much better than conventional ones.

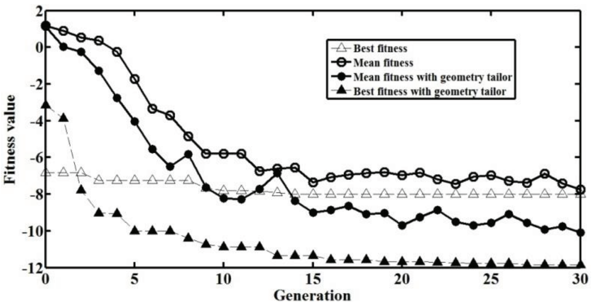

Fig. 3. The best fitness and average fitness comparison.

III. SIMULATION RESULT

In order to verify the ultra-wideband property of such metasurface, full-wave simulations are performed with CST. Figure 4 shows the simulated cross- and co-polarization reflection and polarization-conversion ratio versus frequency. As shown in Fig. 4, strong cross-polarization reflection occurs under both y-polarized and x-polarized normal incidences. Furthermore, the cross-polarization reflection band is very wide. The 3 dB bandwidth is from 5.44 GHz to 24.68 GHz for both y-polarized and x-polarized incident waves. As mentioned above, the ultra-wideband property is resulted from the three plasmon resonance frequencies at 7.23 GHz, 11.88 GHz, and 23.16 GHz, where the polarization conversion efficiency is nearly 100%, as shown in Fig. 5, a 1:4.3 3 dB bandwidth can be achieved for both normally incident x- and y-polarized waves.

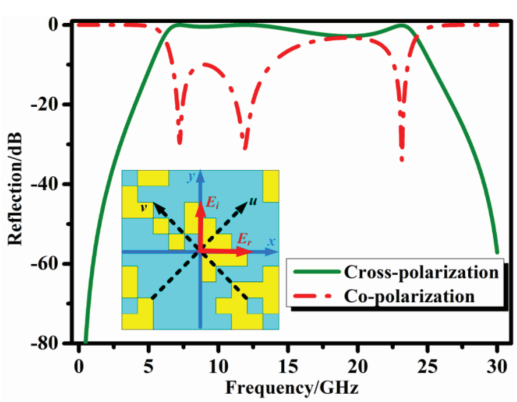

Fig. 4. The cross-polarization and co-polarization reflection.

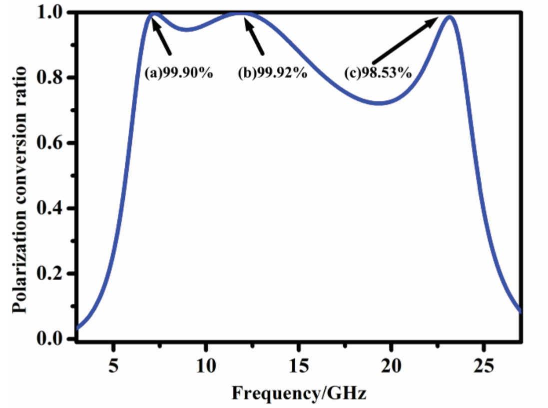

Fig. 5. The polarization conversion ratio.

IV. EXPERIMENT RESULT

To confirm the proposed polarization conversion metasurface, a 320×320 mm^2 sample of the proposed metasurface is fabricated and measured. The experiment system is demonstrated in Fig. 6, in which the sample is illuminated by two vertical horns antenna, so the cross-polarization ratio can be measured. The sample is fabricated by PCB technology. Figure 7 shows the measured results, which are measured by several horn antennas of different working band, ranging from 1 to 30 GHz. Through the comparison of the available results, we can conclude that the measurements are well corresponding with the simulation result.

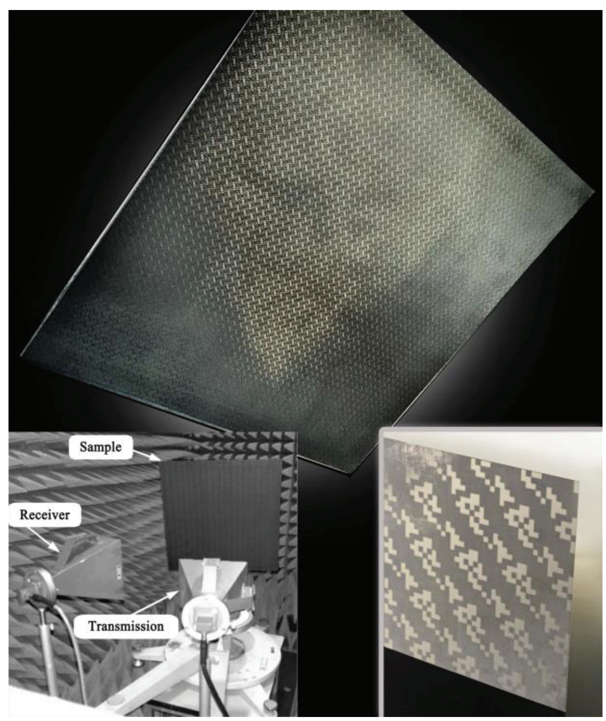

Fig. 6. The fabricated sample of design metasurface and its measurement system.

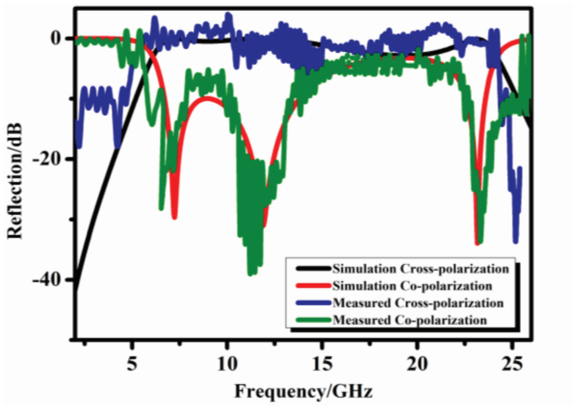

Fig. 7. The measured cross-polarization and co-polarization reflection.

V. CONCLUSION

In conclusion, by means of simulation, we demonstrate that UPCM can be realized using reflective metasurfaces at microwave frequencies by topology design. Due to multiple electric and magnetic resonances, cross-polarization reflection bandwidth can be expanded significantly. An improved topology with GTS has been proposed to achieve better design of UPCM. As an explicit example, we designed and verified a UPCM with a 1:4.3 3 dB bandwidth. Furthermore, the maximum conversion efficiency is up to 100% at the three plasmon resonance frequencies. Because of the easy design, such polarization conversion metasurfaces are of great application values in the polarization controlled devices and other MMs.

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Sai Sui received his master degrees from the Air Force Engineering University of China. His research interests include metamaterial of electromagnetic wave design and optimization design.